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Abstract. This paper proposes an integrated approach for sustainable supply chain planning. Inspired by both researches on performance measurement and supply chain planning, we designed a three-step based approach to measure sustainability performance, and we transposed it to a multi-objective mathematical programming. The three-step based approach ensures coherency while the mathematical model allows the operationalizing and the optimizing of the supply chain performance following the three dimensions of sustainability (economy, environment, and society). Encompassing the three afore-mentioned dimensions and neglecting none is indeed the core motivation of our approach. The supply chain is modeled as a network of activities in order to capture the characteristics of the production system and to have "good" performance accuracy. We have considered the original case of divergent manufacturing processes where a multitude of output products are obtained from one common product. We applied our integrated approach to a realistic case inspired by the Canadian lumber industry and we resolved the mathematical model by using the weighted goal programming technique. Our results provide a set of "compromise" solutions allowing the decision maker to choose the alternative that reflects his/her wishes best regarding the three dimensions of sustainability performance.

Keywords. Supply chain planning, sustainability performance measurement, multi-objective mathematical programming, activity network, divergent processes modeling.

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1. Introduction

The growing public concern about environmental issues in our contemporary era goes hand in hand with an emerging distrust of a certain pattern of economic development that causes damages to nature, hazards to human health and leads, furthermore, to an unfathomable social inequality. As a consequence, there had been and still is a strong demand for product traceability (carbon footprint, product composition and disposal, working conditions in supplier countries, etc.) and a tightening of government regulations (European WEEE directive, carbon tax, etc.). In order to meet these requirements, companies have begun to incorporate sustainability concerns in the management of their operations by relying on corporate social responsibility (CSR) practices. CSR is "a concept whereby companies integrate social and environmental concerns in their business operations and in their interaction with their stakeholders on a voluntary basis" [1]. Recent studies suggest that a strategy based on CSR is a differentiating factor [2], [3] and its implementation would improve the relationships of a given company with its stakeholders while improving its profitability at the same time [4]. Yet, studies quantifying the impact of such an approach and analyzing the relationship between environmental protection, social welfare and economic viability in an integrated way are quite rare in the literature.

Our research aims at contributing to the improvement of the afore-mentioned situation. We address the problem of the operationalization and the optimization of sustainability performance when planning the supply chain (SC) (i.e. sustainable SC planning) at all levels (strategic-tactical-operational). To achieve this goal we relied on both researches on performance measurement and operations research (OR). The mutual enrichment of the two disciplines led us to propose an integrated approach that allows us to, first, specify the sustainability performance we want to measure (what to measure?), second, to link the criteria (objectives) of sustainability performance to the SC planning decisions (how to operationalize?), and finally, to assess and optimize the SC sustainability performance (how to measure and how to optimize?). To achieve this end, the production system involved in the SC needs to be modeled in such a way that its characteristics could be adequately captured and the performance measured with a good accuracy. We therefore model the SC as a network of activities [5].

We propose a framework including three main phases. In the first one (Phase I), we designed a generic three-step approach for sustainability performance measurement. In the second phase (Phase II), we represented the production system as a network of activities. We finally modeled, in the third phase (Phase III), the SC planning problem by using a multi-objective

mathematical programming (MOP) to optimize the SC performance regarding the three dimensions of sustainability. Indeed, reducing all dimensions to one single objective is not desirable [6]. MOP allows not only to "optimize" the SC sustainability performance but also to analyze its behavior when operating different preferences (trade-offs) for the economic, environmental, and social dimensions. MOP could help the decision maker to make enlightened decisions according to the (possible) SC sustainability performance level he/she wants to achieve, on the one hand. The decision maker would be, on the other hand, aware of his/her degrees of freedom enabling him/her (or not) to engage in CSR. He/she could, for example, know precisely the additional cost he/she should pay in order to achieve a certain level of environmental and/or social performance.

We illustrate our integrated approach by applying it to a realistic tactical planning problem inspired by the Canadian lumber industry. This kind of industry involves divergent manufacturing processes since a multitude of output products could be obtained from one common product [7], [8]. In addition to that, several cutting patterns could be applied to get different mix of products. These characteristics are common to, among others, the meat and metal sheet industries. Given these particular features, modeling the production system as a network of activities appears to be the most suitable choice. We solved the MOP using the weighted goal programming technique. The remainder of the paper is organized as follows: the next section (2) introduces SC planning and sustainability, performance measurement and we it also presents a brief literature review. In Section 3, we will present our integrated approach. Section 4 is dedicated to the mathematical formulation. Section 5 introduces the case study and presents our experimentation and results. Finally, we will draw some conclusion and give insights on our future work in section 6.

2. Supply chain planning and sustainability: concepts and a brief literature review

This section aims at sketching the current penetration of sustainability concerns into the literature on SC planning and how operational research (OR) has been used to handle such planning problems. Following this literature review we will show that SC sustainability needs to be linked to the "concept" of performance measurement. This section will therefore be separated into three parts. The first one provides a brief introduction to SC planning and sustainability. The second part presents our literature review. Finally, in the third part we recall the basics of performance measurement.

2.1 Supply chain planning and sustainability

A SC may be defined as the processes that start from the initial raw materials up to the ultimate consumption of the manufactured product. These processes link supplier-companies to user-companies (i.e. suppliers, manufacturers, distributors, retailers, etc.). SC planning is concerned with the determination of a set of policies that govern the operations of the SC [9]. Three levels of planning can be distinguished on the basis of time horizon; namely, strategic, tactical and operational [10]. Strategic planning models aim at identifying the optimal timing, the location and the extent of additional investments needed to operate the SC over a relatively long time horizon (5 to 10 years). Short-term operational planning models constitute the other extreme of the spectrum of planning models. They are characterized by very short timeframes, such as 1 or 2 weeks, over which they address, the optimal routing of vehicles or the optimal sequencing of the manufacturing tasks, etc. Tactical planning models fall in between these two extremes. They address mid-term horizons and incorporate some features from both the strategic and operational models. For instance, they account for the carryover of inventory over time much like the scheduling models and, in spirit with the strategic planning, they consider the presence of multiple facilities in the SC [11].

In the SC planning literature, the focus is usually drawn on the economic performance (cost, profit, responsiveness, etc.). However, with the consumers' increasing awareness about sustainability issues, and due to the tightening of legislation in this regard, several studies on sustainable SC emerged in the literature. Sustainable development is "a development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [12]. For instance, the implementation of legislation making industrials responsible for the collection, treatment, recycling and environmentally safe disposal of their products such as European Union WEEE Directive led to design reverse SCs (or reverse logistics) including a reverse flow of materials [13], [14]. Although reverse logistics bring a partial answer with regard to waste management, it appears necessary to go beyond and to operationalize sustainability in its whole. The operationalization of sustainable development lies on the triple bottom line approach, where a minimum performance is to be achieved in the economic, environmental, and social dimensions (Profit, Planet, and People).

2.2 Literature review

We will report, here, on how sustainability concerns have been considered in the literature, at the strategic/tactical planning level first, and then at the tactical/operational level.

At the strategic/tactical level, all the papers we examined took into account economic aspects such as cost, profit, responsiveness, etc., but only 30% of them considered environmental

criteria, and less than 10% integrated social aspects. Environmental criteria were tackled in particular in works studying reverse logistics ([15], [16], [17], [18], [19], etc.). For instance, Fonseca et al. (2010) [18] minimized the resulting obnoxious effect (odors, noise, etc.) of landfills to be located. Pati et al. (2008) [16] considered pollution reduction through high waste recovery. Moreover, CO_2/greenhouse gas (GHG) emission is the environmental criterion most often considered in the literature. Wang et al. (2011) [20] associated different CO_2 emission levels to potential suppliers, modes of transportation and manufacturing technologies to be selected in the SC. Luo et al. (2001) [15], Dotoli et al. (2005) [21], and Dotoli et al. (2006) [22] have all optimized an integrated e-SC (i.e. SC involving e-commerce, electronic linkages, and material flows) where CO_2 emissions and energy use amounts were associated to the various e-SC linkages. Chaabane et al. (2012) [19] associated GHG emissions to the (re)manufacturing technologies and transportation modes to be selected in the SC.

Regarding social issues, only potential long-term damage to human health (end-point impact caused by climate change, ozone layer depletion, etc.) was taken into account, and this was done only by very few studies that used the life-cycle analysis approach (LCA). LCA is indeed by far the most used approach in the literature when it comes to take into account socio-environmental criteria ([23], [17], [24], [25], [26], [19], etc.). The LCA method first quantifies energy, and globally used inputs and released waste at every stage in product life cycle (often restricted to production, transportation, storage, recycling, and disposal when applied to the SC). The information is then translated into a set of environmental impacts categories such as global warming, resource depletion etc., and an indicator is set to each category of impact [25]. The indicators could further be aggregated into one single indicator that captures the global environmental impact such as Eco-indicator 99[1][27]. Eco-indicator 99 was used for example in ([23] [24] [25]).

At the tactical/operational planning level, we observed again that very few studies including sustainability criteria were proposed. In fact, most of the works dealt with CO_2 emissions, while the social dimension, to the best of our knowledge, remained absent. CO_2 emission was integrated as a constraint (carbon emission limitation) into the models or as a cost (and profit under the cap-and-trade system[2]) [28]. Ubeda et al. (2011) [29] minimized the CO_2 emissions of a distribution SC through the re-planning of a capacitated vehicle routing problem and then

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[1] Eco-indicator 99 is an aggregation measure of three environmental damages: (1) damage to human health, (2) damage to ecosystem quality, and (3) damage to resource depletion.

[2] A firm is allocated a limit on CO_2 emissions. If its emission amount exceeds the carbon cap, it can buy the right to emit extra carbon from the carbon trading market. Otherwise, it can sell its surplus carbon credit [34].

a vehicle routing problem with backhauls. Pan (2010) [30] proposed a mathematical model to minimize cost or to minimize carbon emissions when designing different mutualized network configurations in the retail context. Venkat (2007) [31] studied the impact of lot size on CO_2 emissions in a two-stage SC including two storage facilities. Benjaafar et al. (2010) [28] proposed lot sizing models for single and multiple firms (i.e. firms that operate within a SC consisting of other firms that serve as either suppliers or customers) incorporating carbon emissions. They considered four policies based, respectively, on a strict carbon cap, a tax on the amount of emissions, the cap-and-trade system and the possibility to invest in carbon offsets to mitigate carbon caps. Tao et al. (2010) [32], Bonney and Jaber (2011) [33], Hua et al. (2011) [34], and Bouchery et al. (2012) [6] have all extended the classical economic order quantity (EOQ) model to take into account carbon emissions.

We conclude that there is an obvious lack of works that take into account all the three dimensions of sustainability at once in the SC planning literature. Even though the term "sustainability" is used in several works to qualify the proposed models, the meaning of sustainable development is poorly reflected into these models since very little attention has been paid to the social dimension. In order to fill the lacunae of this situation, we believe that a set-back on performance measurement is needed. In fact, although the performance criteria such as cost and SC responsiveness are quite well addressed in the literature [35], criteria related to sustainable development are marginalized. It appears therefore necessary to look at the literature on performance measurement involving multiple criteria and dimensions (economy, environment, and society).

2.3. Performance measurement

In what follows, we will briefly describe the principles of the most popular methods and models designed for the (sustainability) performance measurement.

Traditionally, the common attributes considered for the performance measurement are tied to financial aspects (cost, return on investment, etc.), flexibility (flexibility of production, distribution, etc.), responsiveness (lead time, cycle time, etc.), reliability (reliability of forecasts, delivery service level, etc.), and quality (quality of production, service quality, etc.) [36]. Early contributions involving multiple criteria for the performance measurement were proposed in the 1980s. For instance, Globerson (1985) [37] proposed an approach based on four steps: (1) identification of the critical performance criteria (2) establishment of performance indicators, (3) definition of targets to be achieved for each criterion using benchmarking, and (4) design of a control loop to correct the deviations from the targets. Since then, many contributions appeared in the literature. Some of them, in particular, being

in line with CSR issue, included sustainability performance criteria. Indeed, performance measurement needs to be adapted to the sustainability context [38]. It should be extended to all the three dimensions to encompass not only economic criteria but also environmental and social ones such as pollution, social equity, etc.

Based on the business activities/processes, ABC/ABM methods (Activity-Based Costing and Activity-Based Management, respectively) [39] introduced the concept of "performance inducers" aiming at identifying the factors that could improve the performance of the business activities/processes. ECOGRAI method [40] aims at designing and implementing a coherent performance indicator system. It is based on the triplet (objective, decision variable, indicator) where decision variables are the variables on which the decision maker could act in order to achieve the objectives. The balanced scorecard (BSC) [41] attempts to balance the performance following four axes (financial, customers, internal business, and learning & growth). It considers within each axis the objectives to be achieved, measures (performance indicators), targets, and initiatives. Later, several works proposed to include sustainability criteria to the BSC such as [42], [43], etc. For instance, Bieker [43] suggested adding a fifth axis: society. He proposed within this axis, a set of "sustainability" indicators such as expense amounts in collaborative campaigns, lobbying and technology transfer, etc.

The Quantitative Model for the Performance Measurement System (QMPMS) developed by Bititci (1995) [44] is based on the identification of action variables that would impact performance. These impacts are then quantified using the AHP method [45], and finally aggregated by operating a weighted sum. The Supply Chain Operations Reference Model (SCOR) aims at evaluating and improving SC performance based on the best practices and five generic metrics (reliability, responsiveness, agility, costs, and assets). The best practices are expected to contribute in heightening the performance of the business processes. The latest version of SCOR [46] introduced the referential GreenSCOR. This latter highlights a number of best practices related to CSR (environmental management system implementation, recyclable material identification, load maximization, etc.) as well as a set of environmental indicators such as GHG emission, percentage of waste recycled, liquid waste generated, etc.

The main conclusion that could be made regarding the approaches proposed in the literature for the performance measurement (including or not sustainability criteria) is that they are all based on three invariants forming a triplet: (1) performance criteria specification, (2) identification of variables impacting the performance, and (3) performance indicator definition. However, three main drawbacks could be highlighted:

- Except very few methods such as QMPMS, all the rest are purely qualitative. The quantification of the performance indicators is not specified and the action variables are not linked directly to the indicators using quantitative expressions for example.
- The targets to be achieved for each performance objective (or criterion) are set based on the experience, benchmarks, etc.
- The methods proposed are not predictive. The performance could be measured and corrective actions can be undertaken only once the performance measurement system has been implemented.

Relying on the performance measurement approaches, we propose a framework presenting an integrated approach, to better apply OR tools in dealing with sustainable SC planning. Our framework and integrated approach are presented in the next section.

3. Sustainability supply chain planning: an integrated approach

The analysis of the recent literature led us to conclude that, although OR researchers succeeded in proposing accurate formulations to model SC planning problems, they have failed in addressing all the three dimensions of sustainability performance at once. We believe that performance measurement approaches could provide an interesting framework to OR tools such as MOP in dealing with sustainability performance measurement while ensuring coherency. Moreover, MOP technique could enrich the performance measurement literature as well, by providing a powerful quantitative tool allowing the operationalization of the performance and its optimization. Inspired by the two domains of research, we propose a framework (Figure. 1) presenting an integrated approach for sustainable SC planning where:

(i) The three invariants of the performance are adopted since they lay the foundations of the performance measurement.

(ii) The performance indicators are quantified and linked to the SC planning decisions using quantifiable expressions.

(iii) The targets to be achieved for each performance objective are set to their best possible attainable values (i.e. the optimums).

(iv) The performance behavior could be predicted and adjusted following the wishes of the decision maker, since different trade-offs could be obtained.
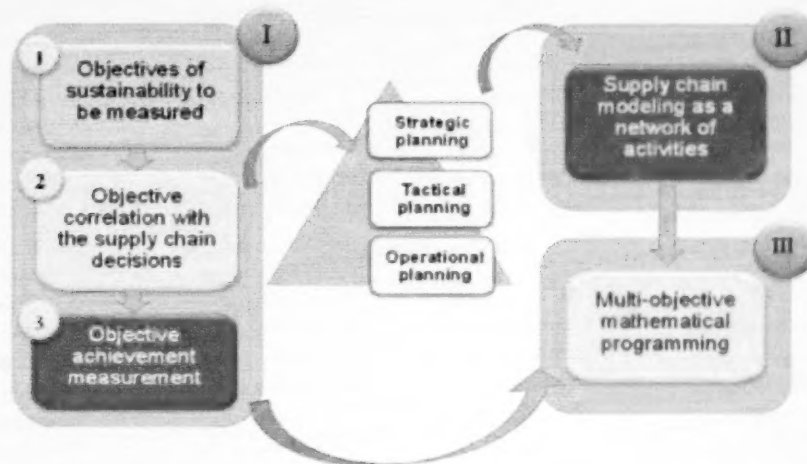
Figure. 1: A framework for sustainable supply chain planning

3.1 A three-step based approach for sustainability performance measurement

Inspired by the performance measurement literature, we propose an approach encompassing three steps (Figure. 1. I): (1) identify the objectives of sustainability to be measured, (2) correlate the objectives with the SC planning decisions, and (3) set the performance indicators to measure the achievement of each objective. This three-step based approach presents the advantage of being generic and independent from the involved SC planning level.

3.1.1 Sustainability objective identification

To identify relevant objectives, we relied on the scientific literature and international standards such as SCOR/GreenSCOR models, OECD guidelines [47], GRI [48], ISO 26000 [49], etc. Inspired by the work of Baumann (2011) [38], we selected 12 objectives to cover the three dimensions of sustainability (Table 1): 5 objectives related to the economic dimension, 4 to the environmental dimension and 3 objectives related to the social dimension.

Table. 1: Sustainability performance criteria (inspired by [38])

Dimension	Economy (Eco)	Environment (Env)	Society (Soc)
Objective	Improve financial performance[1]	Reduce resources consumption[1]	Preserve health and security of employees[1]
	Improve responsiveness[2]	Reduce GHG emission[2]	Create job and wealth[2]
	Improve flexibility[3]	Reduce pollution[3]	Ensure good conditions of work[3]
	Improve reliability[4]	Manage hazardous materials[4]	
	Improve quality[5]		

3.1.2 Objective correlation with the SC planning decisions

Once the objectives are set, their links to the SC planning decisions need to be analyzed. In fact, when planning the SC, the action variables that may impact on the SC performance are the decisions to be made. At the strategic level, for example, the location of a production site

could impact on the production cost, the delivery time, the GHG emissions, and even the employment level in the region. At the tactical level, closing a business unit during one or more periods could affect the level of employment and responsiveness. At the operational level, the choice of a scheduling plan could impact on cost, delivery, flexibility, and stability of employment.

3.1.3 Objective achievement measurement

To assess the achievement of each objective, we examined the existing sustainability performance indicators in the scientific literature and international standards [50], [51], [52], [46], [47], etc.

3.2. Supply chain modeling as a network of activities

To describe a manufacturing system, two approaches are adopted in the literature: the material balance approach and the activity-based approach [53]. In the former the needs for raw materials and intermediate products are calculated without taking into account the specificities of the activities (technologies) that transform the products. The activity-based approach considers that an activity consumes several resources such as employees, energy, water, etc., in order to transform input products to output products using a certain technology that specifies how the inputs are transformed into outputs ([5], [53] and [19]). Undesirable outputs, such as waste, CO_2 and other emissions could be generated as well. Moreover, the activities could present a divergent or a convergent BOM [54]. In addition, the input products could be cut or combined in different ways, when a certain technology is used (e.g., recipes in pulp and paper industry, bucking or sawing patterns in lumber industry, cutting patterns in meat industry, etc.) (see Figure. 3 in section 4). As in [53], we associate to each technology a single activity. By doing so, we define a relationship of bijection between the technology and the activity. We therefore consider as many distinct activities as the existing number of technologies. We also associate several recipes to each activity.

3.3 Multi-objective mathematical programming

The three-step based approach is finally transposed to MOP that operationalizes and optimizes the performance of the SC modelled as a network of activities, following the three dimensions of sustainability. Indeed, reducing all the aspects of sustainability to one single objective is not desirable [6]. The decision maker would be interested in having individual performance indicators for each dimension of sustainability for the purpose of understanding, controlling, benchmarking, communicating, etc. The analysis of the interrelations between the different objectives could also be crucial: "Is it possible to have a 'win-win' situation where the performance is balanced between the three dimensions?", "How much would it cost to

reach a certain environmental/social performance level?" etc. MOP is suitable since its resolution (when using an appropriate multi-objective decision making method) leads to a set of "compromise" solutions (i.e. Pareto solutions) from which the decision maker could choose the solution that best reflects the compromise he/she wishes to make. We present in the following section the MOP we formulated for the tactical planning of a SC involving divergent processes.

4. A multi-objective mathematical programming for the tactical planning of a divergent process based supply chain

In this section, we are going to show how the three-step based approach can be transposed to a SC planning problem modeled using MOP. For the purpose of illustration, we have considered a tactical planning problem of a SC involving divergent processes. The problem could be formulated as follows: "Given the customer's demand and the available SC resources (materials, machine, labor, storage capacity, etc.), how could sustainability concerns be integrated into tactical decision-making with regard to procurement, production, inventory, transport, employment policy etc., while optimizing the SC performance (economic, environmental, and social), on the one hand and meeting, on the other hand, the customer's demand without exceeding the available capacities?"

We will consider a multi-echelon SC including multiple potential suppliers and subcontractors for the procurement of raw materials and intermediate products, multiple production facilities, and various customer zones. Moreover, multiple regions are considered for potential hiring of employees. Several manufacturing technology alternatives are implemented in the facilities, and each activity presents multiple recipes. We will focus on the divergent case, given the fact that only little attention has been paid in the literature to this kind of manufacturing processes. The SC operations are managed by a single entity according to "make-to-stock" policy (MTS). We consider the following hypotheses:

- The planning horizon is divided into multiple periods. One period may correspond to several weeks or several months (a quarter for example). Seasonal behavior of the demand/procurement could be thus taken into account.

- The activities could be done in-house or subcontracted during one or more periods if the internal capacity is insufficient or subcontracting costs less. Nevertheless, part of production could be done in-house even if the activity is outsourced.

- The suppliers and subcontractors are the usual partners of the company. Therefore, fixed costs and binary variables related to supplier and/or subcontractor selection are not

required. In addition, multiple suppliers/subcontractors may be selected for the procurement of the same products during the same period (i.e. multiple-sourcing policy).

- Transport is performed by third-party logistics providers (3PL). Transportation modes as well as the potential carriers are known and selected before the beginning of the planning horizon. Fixed costs of transport and binary variables related to carrier selection are thus omitted. Transportation is assumed to be done on truckload basis, so the costs are proportional to the amounts of transported flow.

- Employees are able to perform any production activity within the sites of the SC.

- Employee transfer from one production facility to another during the planning horizon is allowed if the distance between the employee's residence region and the destination site is reasonable.

We will now describe how we transposed the three-step based approach to our MOP.

4.1 Sustainability objective identification

For the purpose of illustration, we elected four sustainability objectives from Table 1. As the social dimension is the weakest pillar of sustainability in the OR literature on SC, we paid a special attention to it. The objectives are:

- Cost reduction (Eco.1) for the economic dimension,
- GHG emission reduction (Env.2) for the environmental dimension,
- Local job promotion (Soc.2.a), and
- Employment stability (Soc.2.b) for the social dimension.

4.2 Objective correlation with the supply chain planning decisions

The variables that may impact on the SC performance are the planning decisions to be made. Given the sets of indexes:

MP	set of processed products. $MP = MP_{sf} \cup MP_f$ with MP_{sf} the set of intermediate products and MP_f the set of finished products.
P	set of all products. $P = RM \cup MP$, where RM is the set of raw materials.
OMP_{sf}	is the set of outsourced products ($OMP_{sf} \subset MP_{sf}$).
S	set of potential suppliers for products $p \in RM$.
SC	set of potential subcontractors for outsourced products $p \in OMP_{sf}$.
F	set of production facilities.
C	set of customers.
K	set of transportation modes.

Note the $K = KSF \cup KSCF \cup KFF \cup KFC$ where KSF is the set of transportation modes from suppliers to production facilities, $KSCF$ the set of transportation modes from subcontractors to production facilities, KFF the set of transportation modes between production facilities, and KFC the set of transportation modes from production facilities to customers.

A	set of processing activities (or technologies).
$As(i)$	set of activities implemented in production facility i.
CP	set of recipes.
$CPa(a)$	set of recipes associated to activity a.
$ACP(r)$	set of activities using recipe r.
$Pr^{in}(r)$	set of products on which recipe r could be applied.
$MP^{in}(p)$	set of products $p' \in RM \cup MP_{sf}$ used to obtain the products $p \in MP$.
$CPin(p)$	set of recipes applicable to product $p \in RM \cup MP_{sf}$.
$CPout(p)$	set of recipes used to obtain product $p \in MP$.
R	set of residence regions of employees
$RS(i)$	set of residence regions where the production facility i could hire its employees.
$SR(j)$	set of production facilities hiring in the residence region j.
T	set of horizon planning periods $T = \{1, 2, ..., n\}$.

The decision variables of our mathematical formulation are as follows:

X_{prait}	quantity of product p consumed by activity a using recipe r in production facility i at period t (i.e. input product of activity a that serves to produce a mix of output products).
I_{pit}	inventory of product p at production facility at the end of period t.
QS_{pfit}	quantity of raw material p sourced from supplier f by facility i at period t.
QSC_{psit}	quantity of intermediate and outsourced product p sourced from subcontractor s by production facility i at period t.
YSF^{k}_{pfit}	quantity of raw material p carried from supplier f to production facility i using transportation mode k at period t.
$YSCF^{k}_{psit}$	quantity of intermediate and outsourced product p carried from subcontractor s to production facility i using transportation mode k at period t.
$YF^{k}_{pii't}$	quantity of intermediate product p carried from production facility i to production facility $i'(i \neq i')$ using transportation mode k at period t.
YFC^{k}_{pict}	quantity of finished product p carried from production facility i to customer c using transportation mode k at period t.
Lab_{jit}	number of employees living in region j and working at production facility i at period t.
LH_{jit}	number of employees living in region j hired by production facility i at period t.
LF_{jit}	number of employees living in region j fired by production facility i at period t.
$LT_{jii't}$	number of employees living in region j transferred from production facility i to production facility i' at period t.

We analyze the potential correlation between each objective of sustainability (Eco.1, Env.2, Soc.2.a, and Soc.2.b) and the decision variables in order to identify how the objectives could be modeled and measured using expressions of these decision variables. By doing so, the sustainability performance could be operationalized and quantified while ensuring coherency. Table 2 shows the expected impact of the decision variables on the objectives. The correlation analysis is not exhaustive and could lead to different ways of modeling. Our aim here is to illustrate how the modelization could be guided by an analysis of coherency.

Table 2. Correlating SC decisions (i.e. decision variables) with the objectives of sustainability

		Decision variables											
		X_{prait}	I_{pit}	QS_{pfit}	QSC_{psit}	YSF^k_{pfit}	$YSCF^k_{psit}$	$YF^k_{pit't}$	YFC^k_{pict}	Lab_{jit}	LH_{jit}	LF_{jit}	LT_{jitt}
Sustainability objectives	Eco.1	x	x	x	x	x	x	x	x	x			
	Env.2	x				x	x	x	x	x			
	Soc.2.a	x		x	x						x	x	x	x
	Soc.2.b	x	x								x	x	x	x

- **Cost reduction (Eco.1)**

The quantities of the input products being consumed, the quantities stored, and the amounts supplied from suppliers and subcontractors as well as the quantities of products transported between the SC business entities may all have an impact on costs. In fact, to each product (raw materials, intermediate products and finished products) could be associated one or more unit costs of acquisition, transport, processing and storage. The number of employees per region could also affect costs since the total number of employees which depend on the quantities being consumed by the activities presents a labor cost. We define unit costs per product and per employee as follows:

CM_{pait} unit consuming cost of input product p by activity a at production facility i at period t.

CI_{pit} unit handling cost of product p at production facility i at period t.

CA_{pft} unit sourcing cost of raw material p from supplier f at period t.

CS_{pst} unit sourcing cost of intermediate product p from subcontractor s at period t.

CTU^k_{pfit} transportation cost of one unit of volume of raw material p (volume per kilometer travelled) from supplier f to production facility i using transportation mode k at period t.

CTU^k_{psit} transportation cost of one unit of volume of intermediate product p (per kilometer travelled) from subcontractor s to production facility i using transportation mode k

at period t.

$CTU^k_{pii't}$ transportation cost of one unit of volume of intermediate product p (per kilometer travelled) between production facility i and production facility i' using transportation mode k at period t.

CTU^k_{pict} transportation cost of one unit of volume of finished product p (volume per kilometer travelled) from production facility i to customer c using transportation mode k at period t.

CL_t unit labor cost at period t.

- **GHG emission reduction (Env.2)**

The quantities of the input products being consumed, the quantities of products transported between the business units and the number of employees by region could all have an impact on GHG emissions. Alternative technologies that transform the input products indeed could generate GHG proportional to the quantities being consumed. In addition, transporting the products using different modes (truck, rail, etc.) may generate significant amounts of GHG, especially when the distances are important. Finally, the movement of people between their living residence and their workplace could also generate GHG depending on the travelled distance. Other variables such as the number of employees hired, fired, and transferred between sites may also have an impact on GHG emissions since they may increase or decrease the total number of employees per production facility. We thus define GHG emission factors for technologies, transportation modes, and for employees as follows:

β_{ap} GHG emission factor of activity a per unit of the product p consumed (CO_2 *equivalent kg*).

μ_{kp} GHG emission factor of transportation mode k per unit of weight of the product p transported and per kilometer travelled (CO_2 *equivalent kg/kg.km*).

α GHG emission factor per employee per kilometer travelled (CO_2 *equivalent kg/km*).

- **Local job promotion (Soc.2.a)**

Local employment level in a given region (local collectivity) could be affected by the total number of employees at the sites located in that region and the number of employees living within the region and working in those sites. Consequently, the number of employees hired, fired or transferred that determines the total number of employees per site may also affect local employment. The quantity of input products being consumed by the activities as well as the number of hires and layoffs may also have an impact on local employment. An activity can indeed use technologies more or less automated requiring thus more or less employees. The need for labor may vary depending on the quantities of products being consumed by the activities. In addition, the recourse to local subcontractors/suppliers promotes local employment in contrast to the situation where foreign subcontractors/suppliers are requested. Moreover outsourcing (i.e. cost subcontracting) may result in a lack of opportunities for

employment. Within our mathematical formulation, we have defined a parameter to specify the labor consumption by an activity:

L_a number of man-hours required for 1 machine-hour of activity a.

- **Employment stability (Soc.2.b)**

The number of hires and layoffs affect directly the stability of employment. Moreover since the quantities of input products being consumed and the amounts available in stock determine the number of employees needed in the production facilities for each period, they have also an impact on the stability of employment. In addition, the number of employees transferred between sites reduces the number of layoffs in the sites of origin and limits the number of hires in the destination sites.

The parameters of the mathematical programming (other than unit costs) are reported in the following:

D_{pct}	demand of customer c for finished product p at period t.
Cap_{ait}	capacity of activity a at production facility i at period t.
$ICap_{it}$	storage capacity of production facility i at period t.
I_{pit}^{min}	minimum inventory of product p at production facility i at the end of period t.
I_{pi}^{init}	initial inventory of product p at production facility i.
$SCap_{pft}$	capacity of supplier f for product p at period t (quantity of products).
$SCCap_{pst}$	capacity of sub-contractor s for product p at period t (quantity of products).
L_a	number of man-hours required for 1 machine-hour of activity a.
$LUCap_t$	capacity of an employee during period t.
θ_{pra}^{in}	capacity of activity a (in hours) required to transform one unit of the product p using recipe r.
$\tau_{rap'p}$	quantity of product p processed by activity a using recipe r from 1 unit of the product p'.
$LabCap_j$	capacity in region j at period t.
Lab_{ji}^{init}	initial number of employees living in region j and working at production facility i.
$VtrCap^k$	transport capacity of mode k in volume (m^3).
$MtrCap^k$	transport capacity of mode k in weight (kg).
d_{fi}^k	distance between supplier f and production facility i when using transportation mode k.
d_{si}^k	distance between subcontractor s and production facility i when using transportation mode k.
$d_{ii'}^k$	distance between production facilities i and i' when using transportation mode k.
d_{ic}^k	distance between production facility i and customer c when using transportation mode k.
dRS_{ji}	distance between region j and production facility i.
ρ_p	unit volume of product p (in m^3).

v_p unit weight of product p (in kg).

4.3 Objective achievement measurement

- The economic objective (Eco.1) is measured by the total SC cost and expressed in terms of monetary units (m.u.). It is measured and "minimized" using (F_1):

$$F_1 = \sum_t [\sum_{i \in F} (\sum_{a \in As(i)} \sum_{r \in CPa(a)} \sum_{p \in Pr^{in}(r)} CM_{pait} \cdot X_{prait}$$

$$+ CL_t \sum_{j \in RS(i)} Lab_{jit} + \sum_{p \in P} CI_{pit} \cdot I_{pit}) + \sum_{f \in S} \sum_{p \in RM} CA_{pft} \sum_{i \in F} QS_{pfit}$$

$$+ \sum_{s \in SC} \sum_{p \in OMP_{sf}} CS_{pst} \sum_{i \in F} QSC_{psit}$$

$$+ \sum_{k \in KSF} \sum_{f \in S} \sum_{i \in F} d_{fi}^k \sum_{p \in RM} CTU_{pfit}^k \rho_p \cdot YSF_{pfit}^k$$

$$+ \sum_{k \in KSCF} \sum_{s \in SC} \sum_{i \in F} d_{si}^k \sum_{p \in OMP_{sf}} CTU_{psit}^k \cdot \rho_p \cdot YSCF_{psit}^k$$

$$+ \sum_{k \in KFF} \sum_{i \in F} \sum_{i' \in F \, i' \neq i} d_{ii'}^k \sum_{p \in MP_{sf}} CTU_{pii't}^k \cdot \rho_p \cdot YF_{pii't}^k$$

$$+ \sum_{k \in KFC} \sum_{i \in F} \sum_{c \in C} d_{ic}^k \sum_{p \in MP_f} CTU_{pict}^k \cdot \rho_p \cdot YFC_{pict}^k] \tag{1}$$

- The environmental objective (Env.2) is measured by the total GHG emissions (kg equivalent CO2) released across the SC. It is calculated and "minimized" using (F_2):

$$F_2 = \sum_t [\sum_{i \in F} (\sum_{a \in As(i)} \sum_{r \in CPa(a)} \sum_{p \in Pr^{in}(r)} \beta_{ap} \cdot X_{prait} + \alpha \sum_{j \in RS(i)} dRS_{ji} Lab_{jit})$$

$$+ \sum_{k \in KSF} \sum_{f \in S} \sum_{i \in F} d_{fi}^k \sum_{p \in RM} \mu_{kp} \cdot v_p \cdot YSF_{pfit}^k$$

$$+ \sum_{k \in KSCF} \sum_{s \in SC} \sum_{i \in F} d_{si}^k \sum_{p \in OMP_{sf}} \mu_{kp} \cdot v_p \cdot YSCF_{psit}^k$$

$$+ \sum_{k \in KFF} \sum_{i \in F} \sum_{i' \in F, i \neq i'} d_{ii'}^k \sum_{p \in MP_{sf}} \mu_{kp} \cdot v_p \cdot YF_{pii't}^k$$

$$+ \sum_{k \in KFC} \sum_{i \in F} \sum_{c \in C} d_{ic}^k \sum_{p \in MP_f} \mu_{kp} \cdot v_p \cdot YFC_{pict}^k] \tag{2}$$

- The social objective (Soc.2.a) is measured by the percentage of employees (%) living in the local community and working in the sites located within the community. If we consider for instance the community j and all the sites i located nearby, local employment is calculated by the expression: $\left[\frac{\sum_i \sum_t Lab_{jit}}{\sum_j \sum_i \sum_t Lab_{jit}} \right]$. This measure is obtained a posteriori after the resolution of the MOP. Local employment is "optimized" using ($F_{3'}$):

$$F_{3'} = \sum_t \sum_{i \in F} \sum_{j \in RS(i)} dRS_{ji} Lab_{jit} \tag{3'}$$

As we have already integrated the minimization of GHG emissions related to the mobility of the persons (proportional to the distance traveled) in (F_2) ($\alpha \sum_t \sum_{i \in F} \sum_{j \in RS(i)} dRS_{ji} Lab_{jit}$), the objective function ($F_{3'}$) could be omitted.

- Employment stability (Soc.2.b) is measured by the total number of hires and layoffs during the planning horizon. It is calculated and "minimized" using the objective function (F_3):

$$F_3 = \sum_t \sum_{i \in F} \sum_{j \in RS(i)} (LH_{jit} + LF_{jit}) \tag{3}$$

The constraints of the mathematical programming are now presented:

$$\sum_{r \in CPa(a)} \sum_{p \in Pr^{in}(r)} \theta_{pra}^{in} X_{prait} \leq Cap_{ait} \qquad \forall i \in F, \forall a \in As(i), \forall t \in T \tag{4}$$

$$X_{prait} = 0 \qquad \forall i \in F, \forall a \in A \backslash As(i), \forall r \in CPa(a), \forall p \in Pr^{in}(r), \forall t \in T \tag{5}$$

$$\sum_{p \in P} \rho_p I_{pit} \leq ICap_{it} \qquad \forall i \in F, \forall t \in T \tag{6}$$

$$I_{pit}^{min} \leq I_{pit} \qquad \forall p \in P, \forall i \in F, \forall t \in T \tag{7}$$

$$\sum_{j \in RS(i)} Lab_{jit} = \sum_{a \in As(i)} L_a \sum_{r \in CPa(a)} \sum_{p \in Pr^{in}(r)} \theta_{pra}^{in} X_{prait} / LUCap_t \qquad \forall i \in F, \forall t \in T \tag{8}$$

$$\sum_{j \in R \backslash RS(i)} Lab_{jit} = 0 \qquad \forall i \in F, \forall t \in T \tag{9}$$

$$Lab_{ji1} = Lab_{ji}^{init} + LH_{ji1} + \sum_{i' \in SR(j), i' \neq i} LT_{ji'i1} - LF_{ji1} - \sum_{i' \in SR(j), i' \neq i} LT_{jii'1} \qquad \forall j \in R, \forall i \in SR(j) \tag{10}$$

$$Lab_{jit} = Lab_{ji(t-1)} + LH_{jit} + \sum_{i' \in SR(j), i' \neq i} LT_{ji'it} - LF_{jit} - \sum_{i' \in SR(j), i' \neq i} LT_{jii't} \qquad \forall j \in R, \forall i \in SR(j), \forall t \in T \backslash 1 \tag{11}$$

$$LF_{ji1} + \sum_{i' \in SR(j), i' \neq i} LT_{jii'1} \leq Lab_{ji}^{init} \qquad \forall j \in R, \forall i \in SR(j) \tag{12}$$

$$LF_{jit} + \sum_{i' \in SR(j), i' \neq i} LT_{jii't} \leq Lab_{ji(t-1)} \qquad \forall j \in R, \forall i \in SR(j), \forall t \in T \backslash 1 \tag{13}$$

$$\sum_{i \in SR(j)} Lab_{jit} \leq LabCap_j \qquad \forall j \in R, \forall t \in T \tag{14}$$

$$QS_{pfit} = \sum_{k \in KSF} YSF_{pfit}^k \qquad \forall p \in RM, \forall f \in S, \forall i \in F, \forall t \in T \tag{15}$$

$$QSC_{psit} = \sum_{k \in KSCF} YSCF_{psit}^k \qquad \forall p \in OMP_{sf}, \forall s \in SC, \forall i \in F, \forall t \in T \tag{16}$$

$$\sum_{f \in S} QS_{pfi1} + I_{pi}^{init} = \sum_{r \in CPin(p)} \sum_{a \in As(i) \cap ACP(r)} X_{prai1} + I_{pi1} \qquad \forall p \in RM, \forall i \in F \tag{17}$$

$$\sum_{f \in S} QS_{pfit} + I_{pi(t-1)} = \sum_{r \in CPin(p)} \sum_{a \in As(i) \cap ACP(r)} X_{prait} + I_{pit} \qquad \forall p \in RM, \forall i \in F, \forall t \in T \backslash 1 \tag{18}$$

$$\sum_{k \in KFF} \sum_{i' \in F, i' \neq i} YF_{pi'i1}^k + \sum_{r \in CPout(p)} \sum_{a \in As(i) \cap ACP(r)} \sum_{p' \in MP^{in}(p)} \tau_{rap'p} \cdot X_{p'rai1} + I_{pi}^{init} = \sum_{r \in CPin(p)} \sum_{a \in As(i) \cap ACP(r)} X_{prai1} + \sum_{k \in KFF} \sum_{i'} YF_{pii'1}^k + I_{pi1} \qquad \forall p \in MP_{sf} \backslash OMP_{sf}, \forall i \in F \tag{19}$$

$$\sum_{k \in KFF} \sum_{i' \in F, i' \neq i} YF_{pi'it}^k + \sum_{r \in CPout(p)} \sum_{a \in As(i) \cap ACP(r)} \sum_{p' \in MP^{in}(p)} \tau_{rap'p} X_{p'rait} + I_{pi(t-1)} = \sum_{r \in CPin(p)} \sum_{a \in As(i) \cap ACP(r)} X_{prait} + \sum_{k \in KFF} \sum_{i'} YF_{pii't}^k + I_{pit} \qquad \forall p \in MP_{sf} \backslash OMP_{sf}, \forall i \in F, \forall t \in T \backslash 1 \tag{20}$$

$$\sum_{k \in KFF} \sum_{i' \in F, i' \neq i} YF_{pi'i1}^k + \sum_{r \in CPout(p)} \sum_{a \in As(i) \cap ACP(r)} \sum_{p' \in MP^{in}(p)} \tau_{rap'p} X_{p'rai1} + \sum_{s \in SC} QSC_{psi1} + I_{pi}^{init} = \sum_{r = CPin(p)} \sum_{a \in As(i) \cap ACP(r)} X_{prai1} + \sum_{k \in KFF} \sum_{i'} YF_{pii'1}^k + I_{pi1} \qquad \forall p \in OMP_{sf}, \forall i \in F \tag{21}$$

$$\sum_{k \in KFF} \sum_{i' \in F, i' \neq i} YF_{pi'it}^k + \sum_{r \in CPout(p)} \sum_{a \in As(i) \cap ACP(r)} \sum_{p' \in MP^{in}(p)} \tau_{rap'p} \cdot X_{p'rait} + \sum_{s \in SC} QSC_{psit} + I_{pi(t-1)} = \sum_{r \in CPin(p)} \sum_{a \in As(i) \cap ACP(r)} X_{prait} + \sum_{k \in KFF} \sum_{i'} YF_{pii't}^k + I_{pit} \qquad \forall p \in OMP_{sf}, \forall i \in F, \forall t \in T \backslash 1 \tag{22}$$

$$\sum_{r \in RCPout(p)} \sum_{a \in As(i) \cap ACP(r)} \sum_{p' \in MP^{in}(p)} \tau_{rap'p} X_{p'rai1} + I_{pi}^{init} =$$
$$\sum_{k \in KFC} \sum_{c \in C} YFC_{pic1}^{k} + I_{pi1} \qquad\qquad \forall p \in MP_f, \forall i \in F \quad (23)$$

$$\sum_{r \in RCPout(p)} \sum_{a \in As(i) \cap ACP(r)} \sum_{p' \in MP^{in}(p)} \tau_{rap'p} X_{p'rait} + I_{pi(t-1)} =$$
$$\sum_{k \in KFC} \sum_{c \in C} YFC_{pict}^{k} + I_{pit} \qquad\qquad \forall p \in MP_f, \forall i \in F, \forall t \in T \setminus 1 \quad (24)$$

$$\sum_{k \in KFC} \sum_{i \in F} YFC_{pict}^{k} = D_{pct} \qquad\qquad \forall c \in C, \forall p \in MP_f, \forall t \in T \quad (25)$$

$$\sum_{i \in F} QS_{pfit} \le SCap_{pft} \qquad\qquad \forall p \in RM, \forall f \in S, \forall t \in T \quad (26)$$

$$\sum_{i \in F} QSC_{psit} \le SCCap_{pst} \qquad\qquad \forall p \in OMP_{sf}, \forall s \in SC, \forall t \in T \quad (27)$$

$$\sum_p \rho_p . YFC_{pict}^{k} \le VtrCap^{k} \qquad\qquad \forall i \in F, \forall c \in C, \forall k \in KFC, \forall t \in T \quad (28)$$

$$\sum_p \rho_p . YF_{pii't}^{k} \le VtrCap^{k} \qquad\qquad \forall i \in F, \forall i' \in F, i \ne i', \forall k \in KFF, \forall t \in T \quad (29)$$

$$\sum_p \rho_p . YSF_{pfit}^{k} \le VtrCap^{k} \qquad\qquad \forall f \in S, \forall i \in F, \forall k \in KSF, \forall t \in T \quad (30)$$

$$\sum_p \rho_p . YSCF_{psit}^{k} \le VtrCap^{k} \qquad\qquad \forall s \in SC, \forall i \in F, \forall k \in KSCF, \forall t \in T \quad (31)$$

$$\sum_p v_p . YFC_{pict}^{k} \le MtrCap^{k} \qquad\qquad \forall i \in F, \forall c \in C, \forall k \in KFC, \forall t \in T \quad (32)$$

$$\sum_p v_p . YF_{pii't}^{k} \le MtrCap^{k} \qquad\qquad \forall i \in F, \forall i' \in F, i \ne i', \forall k \in KFF, \forall t \in T \quad (33)$$

$$\sum_p v_p . YSF_{pfit}^{k} \le MtrCap^{k} \qquad\qquad \forall f \in S, \forall i \in F, \forall k \in KSF, \forall t \in T \quad (34)$$

$$\sum_p v_p . YSCF_{psit}^{k} \le MtrCap^{k} \qquad\qquad \forall s \in SC, \forall i \in F, \forall k \in KSCF, \forall t \in T \quad (35)$$

$$X_{prait}, I_{pit}, QS_{pfit}, QSC_{psit}, YSF_{pfit}^{k}, YSCF_{psit}^{k}, YF_{pii't}^{k}, YFC_{pict}^{k}, LH_{jit}, Lab_{jit}, LT_{jii't} \ge 0 \quad (36)$$

The set of constraints (4) states that production capacity of the activities is limited. Constraints (5) indicate that products can be processed by an activity only in sites where it is implemented. Constraints (6) specify that the storage capacity is limited, and constraints (7) state that there must be a minimum stock at the end of each period. Equations (8) define the relationship between the amount of processed products in a site and the number of employees needed accordingly in that site. Constraints (9) specify that production facilities cannot employ labor in some regions (regions that are considered too far from the sites). Constraints (10) and (11) specify the number of employees working in a given site and living in a given region. Constraints (12) and (13) ensure that the number of layoffs in as site and the number of employees transferred to other sites during a period don't exceed the number of employees in that site during the precedent period (the new hires and employees transferred from other sites cannot be retransferred or fired within the same period). Constraints (14) specify that the number of employees per region is limited. Constraints from (15) to (25) ensure the flow material conservation through the SC while satisfying the customer's demand (constraints (25)) and without exceeding the supplier and subcontractor capacities (constraints (26) and (27) respectively). Constraints (17) and (18) model the raw material flow from suppliers to sits. Constraints (19) and (20) specify the flow of non-outsourced products between sites.

Constraints (21) and (22) specify the flow of potential outsourced products from sites and/or subcontractors to sites. Constraints (23) represent the flow of finished products between sites and customers. The reader should keep in mind that the processes involved in the SC are divergent. We provided a simple example of two production processes in figure 2. Figure 3 details step by step the product flow from suppliers to customers. We focused on the products being consumed (raw material and intermediate products) using different technologies and recipes in contrast to a convergent process case where the focus is usually drawn on the products being assembled (intermediate products and finished products).

Our example (Figure 2) is inspired by the lumber industry. We considered wood rods (α) sourced from one supplier (f), 2 sites (i_1) and (i_2) where the rods are first sawn using one activity (technology) (a_1) and one recipe (sawing pattern) (r_1) to obtain one type of stems (β) (for the sake of simplicity, we neglected the rejects). This type of stems could also be sourced from a subcontractor (s). The stems are then bucked by using the activity (a_2) in the site (i_1) and the activity (a_3) in the site (i_2). One recipe (bucking pattern) (r_2) is applicable by using (a_2) and 2 bucking patterns (r_2) and (r_3) are applicable by using (a_3). One type of planks (δ) is obtained by using (r_2) and 2 types (ω) and (γ) are obtained by using (a_3). Different transportation modes are available (k). The finished products (δ), (ω), and (γ) are shipped to 3 customers (c_1), (c_2), and (c_3) (see Figure. 3). Sets of constraints (28) to (31) limit the volume transport capacity of all transportation modes while the sets of constraints (32) to (35) limit the capacity in terms of weight. Finally, constraints (36) ensure that all the decision variables are continuous and positive

α: stem, β: log of 8 feet, δ: plank 2x4 feet, ω: plank 2x6 feet, γ : plank 1x4 feet
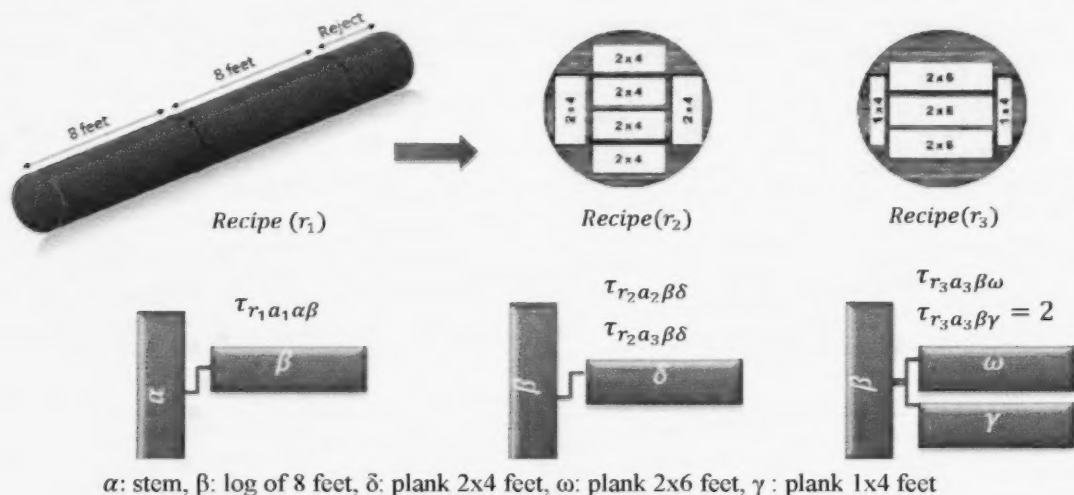
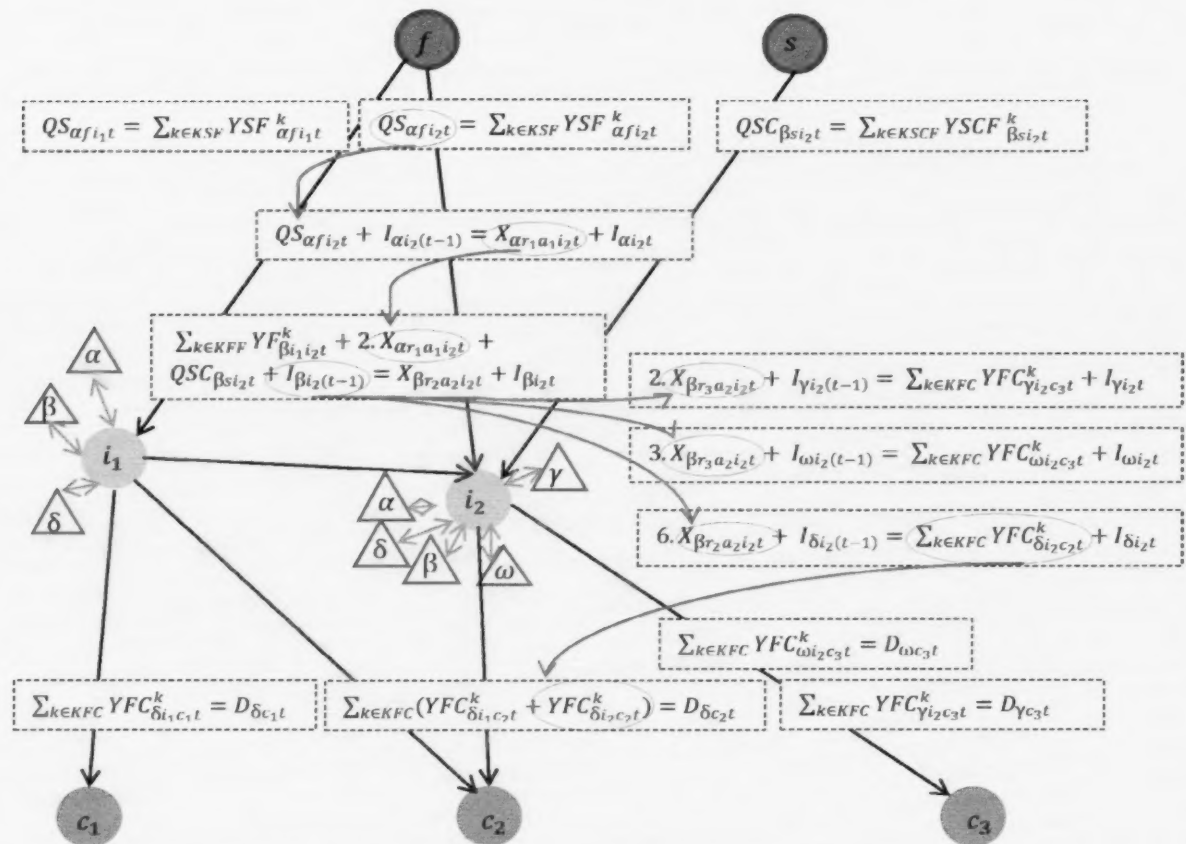Figure 2: An example of two divergent processes, inspired by the lumber industry

Figure 3: Material flow through a supply chain: the case of divergent processes

5. Case study

To illustrate our approach, we relied on a realistic case of a Canadian lumber industry. This case is inspired by the "virtu@l-lumber", and it was developed by Vila et al. (2006) [8] jointly with the three biggest players in the Canadian lumber industry, two Canadian research centers on forestry (FOR@C and Forintek) and the Ministry of Natural Resources and Fauna of Quebec.

The lumber SC under study starts in the forest. Trees are harvested (i.e. they are cut and branches are removed) and then bucked into logs of specific dimensions. Bucking could also be done in the lumber yards. Harvesting is done in two ways: by direct labor (in-house) or under outsourcing contract (forest contractors). Logs, once transported to sawmills, are sawn and planks of different dimensions are obtained (green lumber) depending on the dimension of the logs and on the technologies being used. In fact, different technologies could be selected for bucking and sawing, each of them presenting a set of various applicable cutting patterns. The planks are then dried and the resulting manufactured products (lumber) are shipped to customers. During bucking and sawing, wood residues are also generated. These

latters are chipped and the resulting flakes are sold mainly to pulp and pellet mills. The modes of transportation that could be used to transport the various products from one business unit to another are truck and train.

• Experiments and numerical results

We conducted our experimentation using an instance including 3 forests, 2 potential forest contractors, 3 sawmills, and 5 customers (1 paper mill for flakes, and 4 industrials for lumber). Regarding technologies we considered: 1 bucking technology presenting 3 cutting patterns, 2 sawing technologies presenting respectively 5 and 4 cutting patterns, 2 drying technologies, 1 harvesting technology, and 1 shipping technology. The case study covers 6 periods characterized by demand seasonality. Each period lasts 3 months. We solved our MOP using the weighted goal programming [56]. Each objective function is given a goal (or a target) to be achieved and then the deviations from this set of targets are minimized using a (weighted) deviation sum (achievement function). To set the targets (F_1^*, F_2^*, F_3^*) for the economic, environmental and social objectives $(F_1, F_2, F_3$ respectively), we optimized each objective alone. Each target represents the ideal performance level for the economic, environmental, and social dimensions respectively. In order to harmonize the measurement scales, we have considered the relative deviations (d_1, d_2, d_3): $d_1 = \frac{F_1 - F_1^*}{F_1^*}$, $d_2 = \frac{F_2 - F_2^*}{F_2^*}$, $d_3 = \frac{F_3 - F_3^*}{F_3^*}$, $d_1 \geq 0$, $d_2 \geq 0$, $d_3 \geq 0$. These equalities and inequalities were added as new constraints to the mathematical formulation. We then minimized the weighted sum $(w_1 d_1 + w_2 d_2 + w_3 d_3)$ where (w_1, w_2, w_3) is a vector of weights such that: $0 \leq w_1 \leq 1$, $0 \leq w_2 \leq 1$, $0 \leq w_3 \leq 1$, $w_1 + w_2 + w_3 = 1$. In order to operate different trade-offs, we ranged the weight values between 0 and 1, using a step of 0.1, and ran the model for all the resulting combinations. We used CPLEX 12.2 software on an Intel-Pentium M PC with 1.73 GHz processor and 2 GB RAM. Five minutes were required to solve the MOP. The results are shown in Figure 4. All the solutions present different performance levels following the three dimensions of sustainability allowing the decision maker to choose the one that reflects best his/her wishes. Moreover, it is possible to know exactly the "cost" of a given environmental and/or social performance level since a certain cost (economic performance) corresponds to each couple of environmental and social performance levels. The decision maker could thus know precisely the additional cost that he/she could pay to improve the environmental and/or social performances to a certain level in order, for example, to comply with the regulations and align with the competitors, etc.
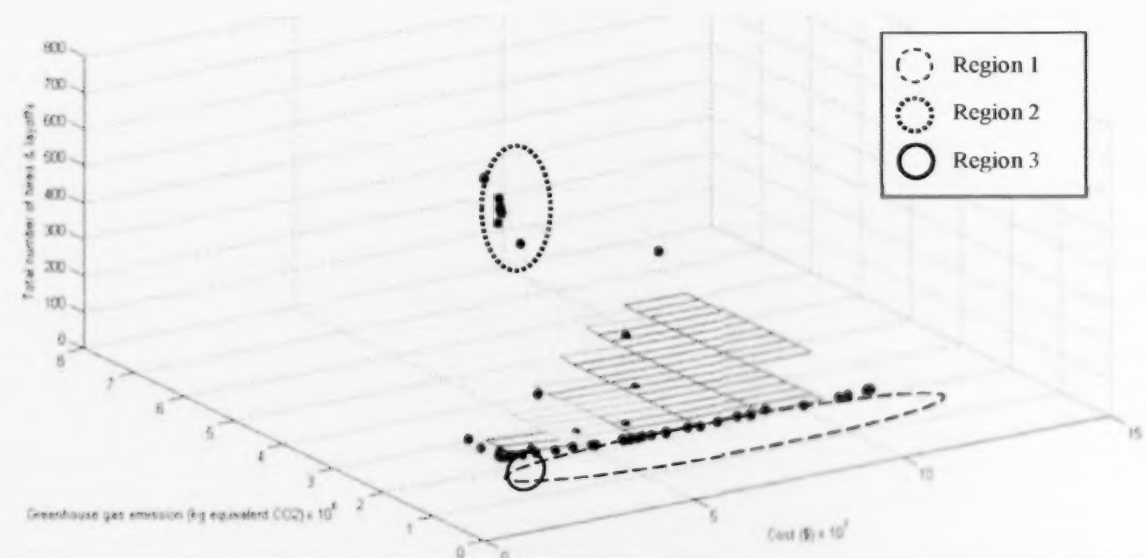
Figure. 4 : Pareto solutions

Three remarkable regions are highlighted in figure 4. Region 1 contains solutions that are relatively stable regarding environmental and social performances but varying widely regarding cost. This means that, for some solutions, a slight improvement of environmental and social performances is costly but unnecessary since there are other solutions presenting comparable environmental and social performance levels and costing much less (e.g. (11.62 x 10^7 S, 20. 29 x 10^8 *kg equivalent* CO_2, 14.36) versus (79.40 x 10^7 S, 19.63 x 10^8 *kg equivalent* CO_2, 16.56)). Region 2 contains solutions with "good" environmental and economic performances but presenting a poor social performance. For instance we found a solution for which the economic and environmental relative deviations were (0.57% and 0.63%) respectively and the social relative deviation greater than 5018%. Globally, we noticed that the gap between the "best" and the worse social performance levels was very high. It was thus difficult to find solutions that present a "good" or reasonable compromise with regard to the social performance.

Finally, region 3 contains the most interesting solutions as the three performances are relatively well balanced. The economic and environmental performances in particular are quite close to their respective targets (the deviations range from 1.88% to 7.87% and from 1.31% to 3.05% respectively). Even within region 3 where the social performance is still far from the target (the deviation ranges from 194.79% to 220.70%), the balance is better in comparison to all other solutions.

6. Conclusion

In this study we propose an integrated approach for the sustainable supply chain planning. To tackle the problem, we have combined the performance measurement approach principles with a multi-objective mathematical programming. We have therefore provided a framework that encompasses three main phases articulated as follows: a three-step based approach allowing sustainability performance measurement is first designed (Phase I). Within this phase we have specified (1) the sustainability objectives (sustainability performance criteria) to be measured, (2) the objective correlation with the supply chain planning decisions and (3) the performance indicators measuring the achievement of the objectives. In Phase II, we have modeled the supply chain as a network of activities to capture its characteristics. Given the characteristics of the supply chain, the three-step based approach is, in Phase III, transposed to a multi-objective mathematical programming that operationalizes the performance and optimizes it following the three dimensions of sustainability.

We have considered the case of divergent manufacturing processes and have illustrated our approach on a tactical planning problem. We have finally applied our approach on a realistic case inspired by the Canadian lumber industry. We have used the weighted goal programming method to resolve the mathematical model. We have obtained a set of solutions presenting different trade-offs regarding economic, environmental, and social performance levels which allow the decision maker to operate the choice that reflects his/her wishes best after sound analyses had been made.

In addition to taking into account the three dimensions of sustainability performance, our approach presents the advantage of being generic: (1) it could be applied to any level of the supply chain planning; what is more (2) other tools, such as simulation, could be used to operationalize the three-step based approach and (3) the production system involved in the supply chain could be modeled using other techniques. We have focused, moreover, on the divergent manufacturing process case that has received little attention in the literature. We have studied a realistic case derived from the Canadian lumber industry where sustainability issues are of primary importance: in recent years forest industry in Canada has evolved in a context of a slowdown (plant closures, job losses, weakening of rural communities, etc.) and under a high pressure exerted by customers, employees, and government. We intend to carry on our research on the forest industry sector. We will focus on the strategic and/or operational planning levels and we will include other criteria of sustainability with a special emphasis on social performance measurement. It would be also interesting to apply our approach, for instance, to other industries involving convergent manufacturing processes.

Acknowledgments

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